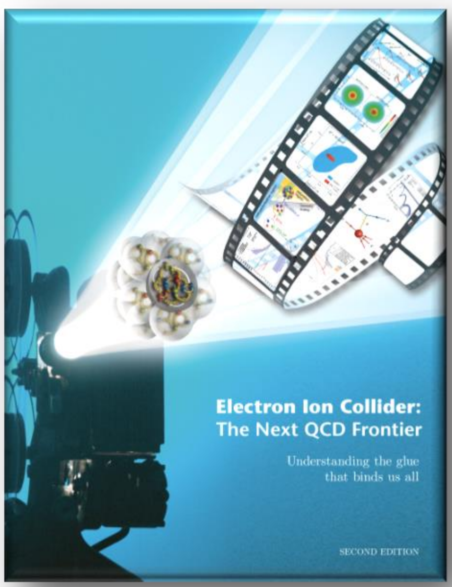
Pion and Kaon Structure Functions



… beyond the science of …

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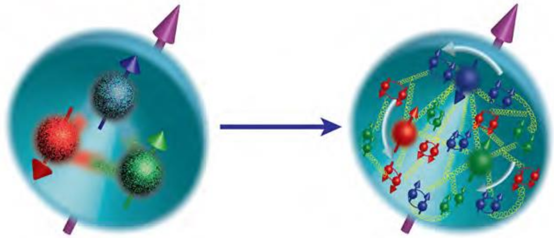
Collaboration with Ian Cloet, Roy Holt, Paul Reimer, Rolf Ent
Thanks to: Craig Roberts, Yulia Furletova and Steve Wood

7th International Conference on Physics Opportunities at an EleTron-Ion Collider

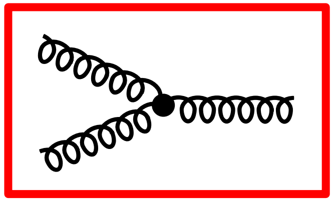
Temple University, 14-18 November 2016

QCD Science Questions

- How are the gluons and sea quarks, and their intrinsic spins distributed in space & momentum inside the nucleon?
  - Role of Orbital Angular Momentum?



- What happens to the gluon density in nuclei at high energy? Does it saturate into a gluonic form of matter of universal properties?

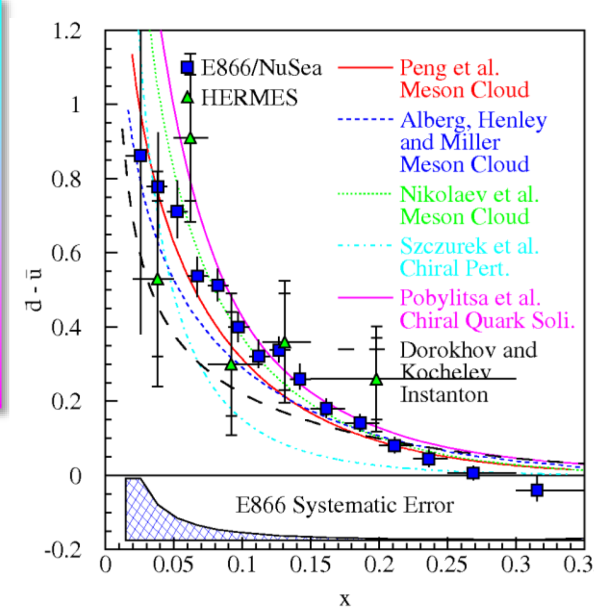


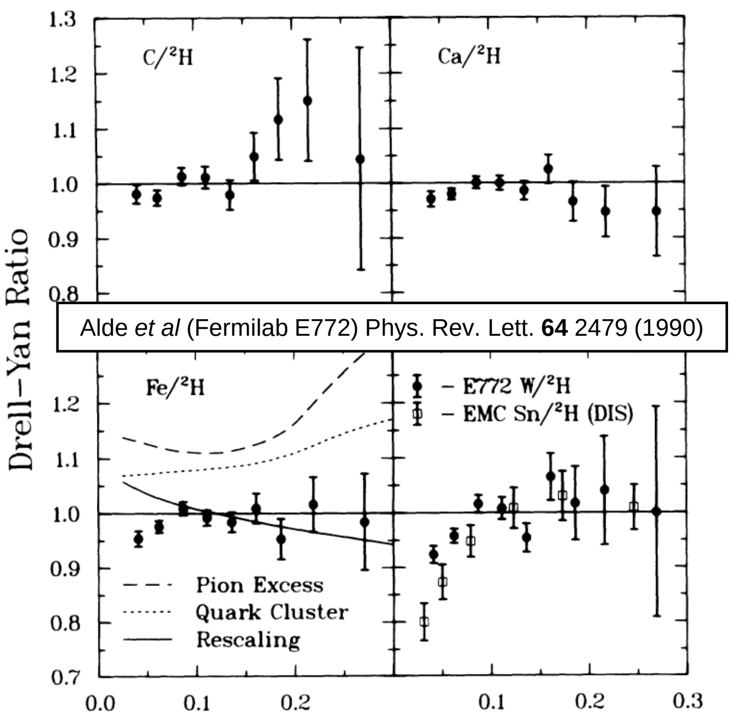
How about the distributions of quarks and gluons in the lightest mesons - pions and kaons?

Why should you be interested in pions and kaons?

Protons, neutrons, pions and kaons are the main building blocks of nuclear matter

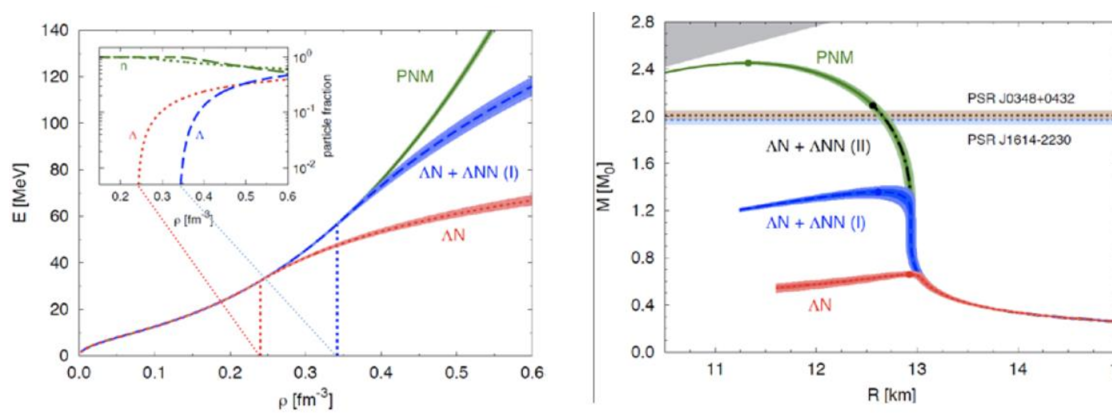
1) The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea
2) Pions are the Yukawa particles of the nuclear force – but no evidence for excess of nuclear pions or anti-quarks
3) Kaon exchange is similarly related to the ΛN interaction – correlated with the Equation of State and astrophysical observations
4) Mass is enigma – cannibalistic gluons vs massless Goldstone bosons





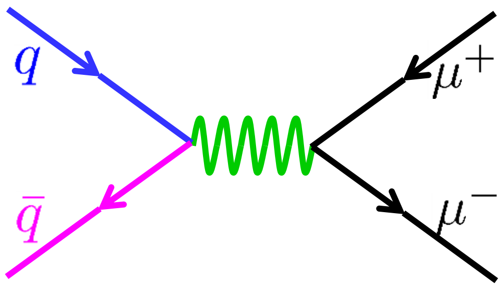
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

Equations of state and neutron star mass-radius relations



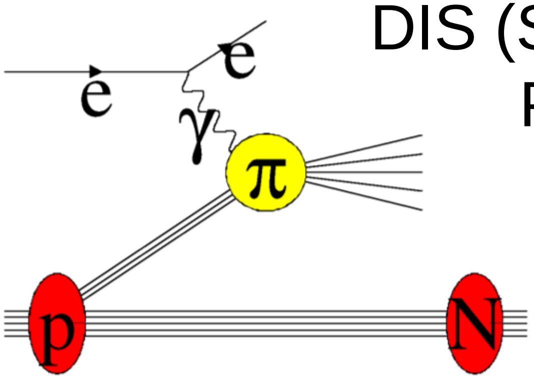
World Data on pion structure function F_2^{π}

Pion Drell-Yan

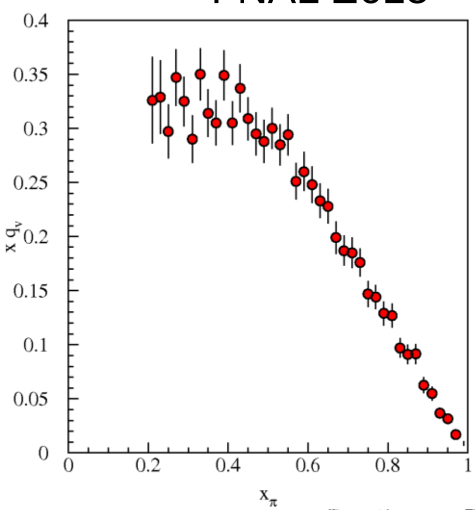


Data much more limited than nucleon…

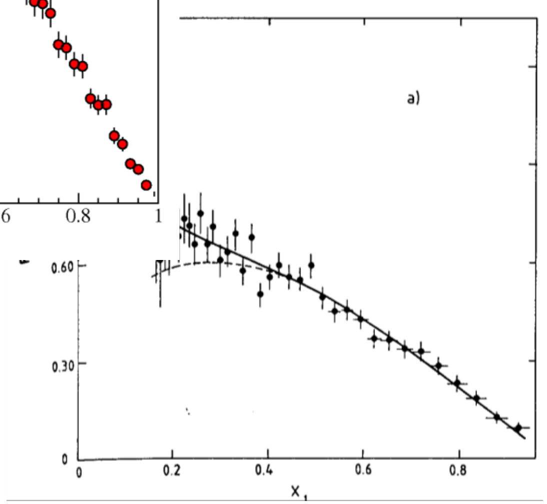
DIS (Sullivan Process)

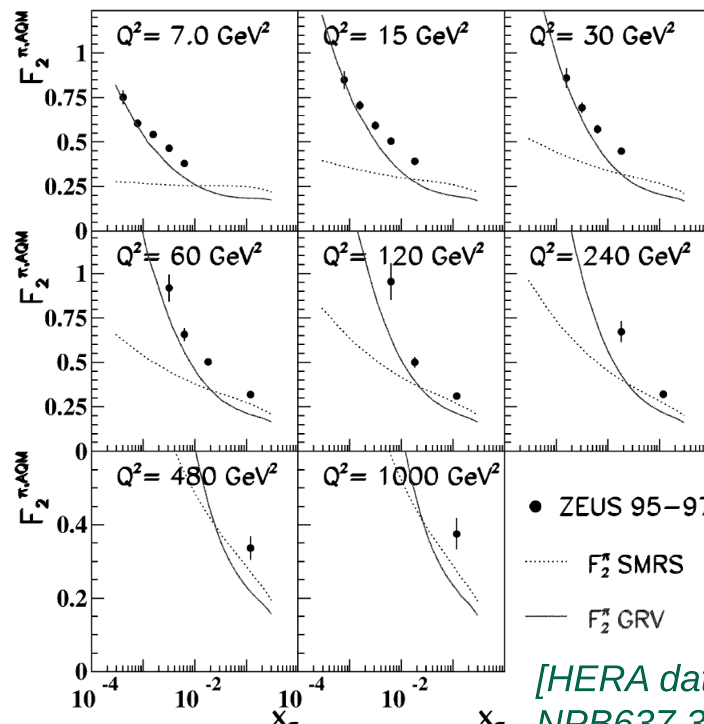


FNAL E615



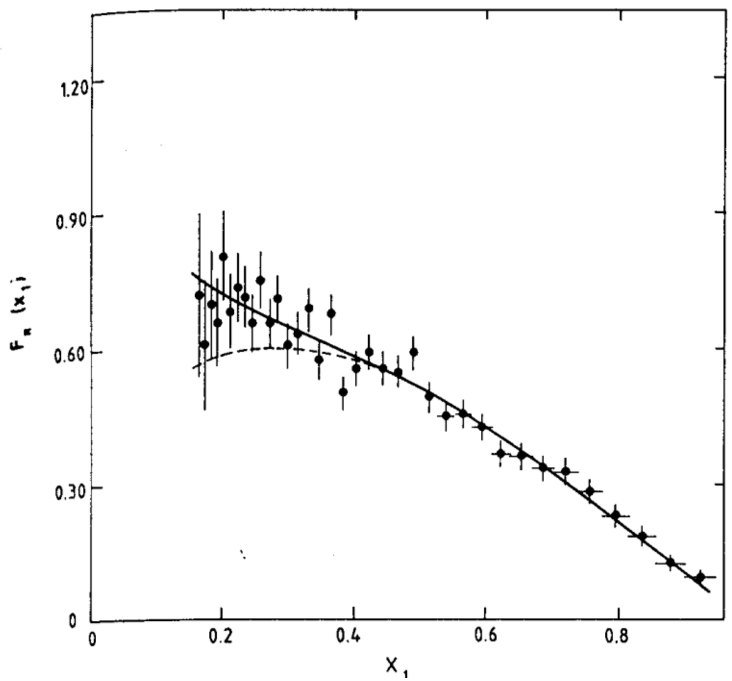
CERN NA3





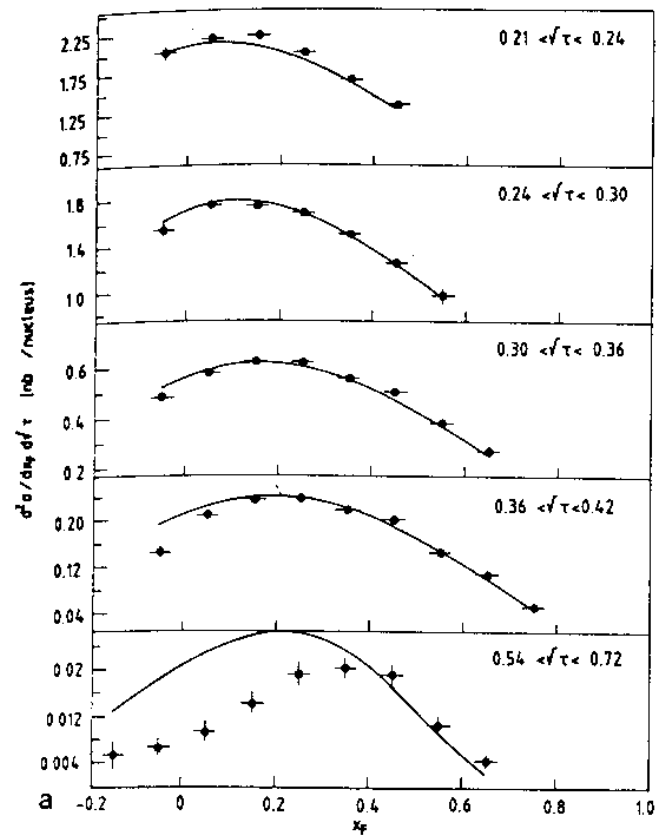
[HERA data [ZEUS, NPB637 3 (2002)]

Pion Drell-Yan Data: CERN NA3 ($\pi^{+/-}$) NA10 (π^-)



NA3 200 GeV π^- data (also have 150 and 180 GeV π^- and 200 GeV π^+ data). *Can determine pion sea*!

$$Q_\pi^{\text{sea}} \equiv \int_0^1 x q_\pi^{\text{sea}}(x) dx = 0.01$$



NA10 194 GeV π^- data

quark sea in pion is small – few %

The role of gluons in pions

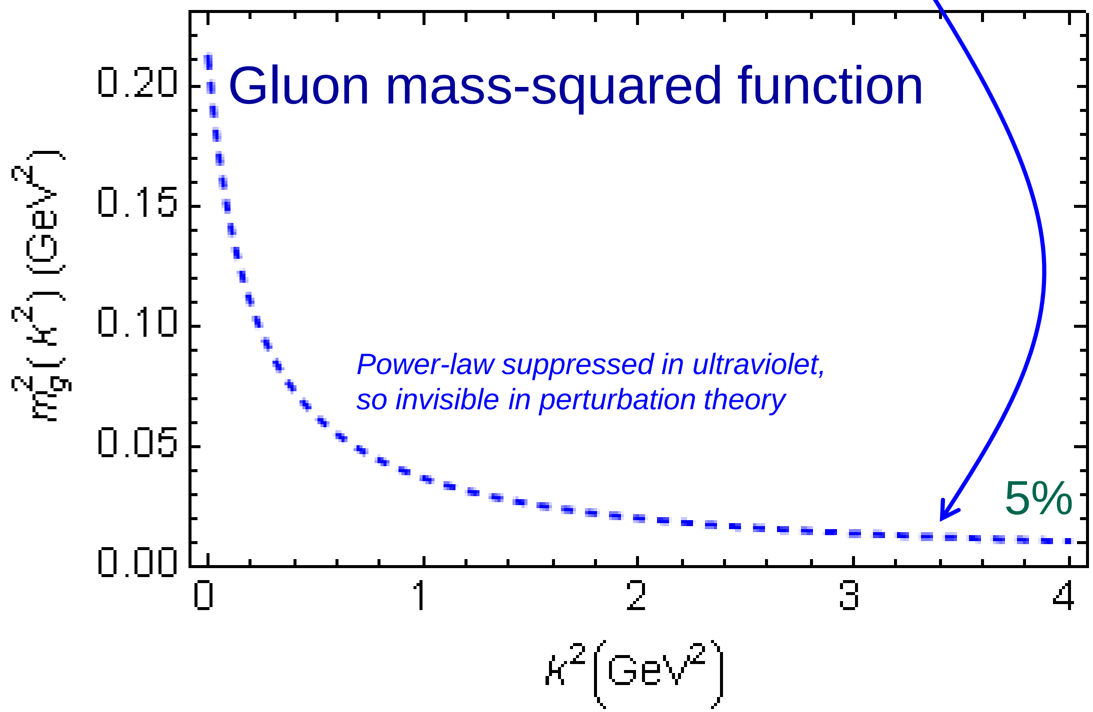
Pion mass is enigma – cannibalistic gluons vs massless Goldstone bosons

$$f_\pi E_\pi(p^2) = B(p^2)$$

$$m_g^2(k^2) = \frac{\mu_g^4}{\mu_g^2 + k^2}$$

Adapted from Craig Roberts:

- ❑ The most fundamental expression of Goldstone's Theorem and DCSB in the SM
- ❑ Pion exists if, and only if, mass is dynamically generated
- ❑ This is why $m_\pi = 0$ in the absence of a Higgs mechanism



What is the impact of this for gluon parton distributions in pions vs nucleons?
One would anticipate a different mass budget for the pion and the proton

See also talk by M. Savage on Monday, 14 Nov

Quarks and gluons in pions and kaons

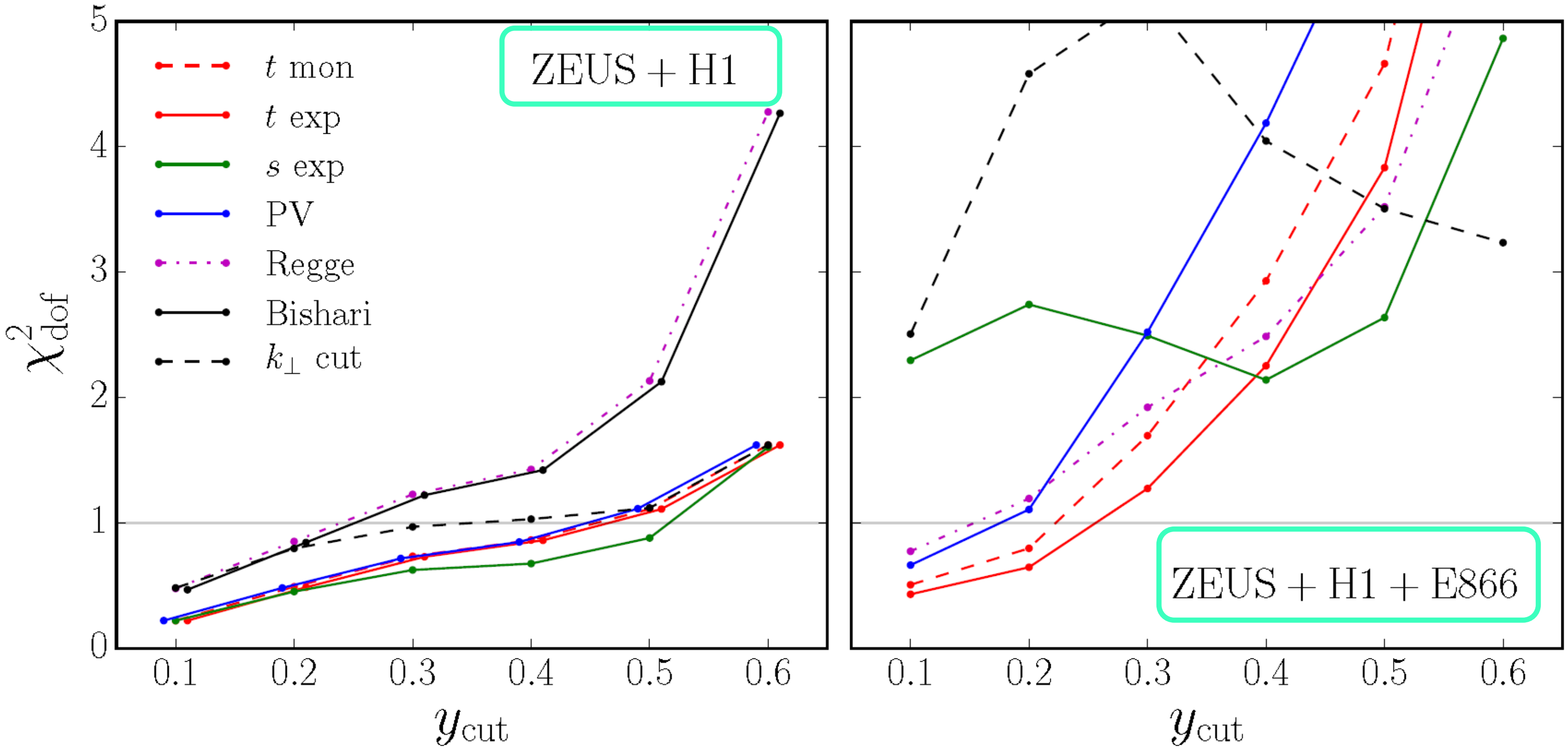
Talk @ ANL EIC UG Meeting: how about the distributions of quarks and gluons in the lightest mesons - pions and kaons?

- At low x to moderate x, both the quark sea and the gluons are very interesting.
  - Are the sea in pions and kaons the same in magnitude and shape?
  - Is the origin of mass encoded in differences of gluons in pions, kaons and protons, or do they in the end all become universal?
- At moderate x, compare pionic Drell-Yan to DIS from the pion cloud
  - test of the assumptions used in the extraction of the structure function and similar assumptions in the pion and kaon form factors.
- At high x, the shapes of valence u quark distributions in pion, kaon and proton are different, and so are their asymptotic x → 1 limits
  - Some of these effects are due to the comparison of a two- versus three-quark system, and a meson with a heavier s quark embedded versus a lighter quark
  - However, effects of gluons come in as well. To measure these differences would be fantastic.

At high x, a long-standing issue has been the shape of the pion structure function as given by Drell-Yan data versus QCD expectations. However, this may be a solved case based on gluon resummation, and this may be confirmed with 12-GeV Jefferson Lab data. Nonetheless, soft gluon resummation is a sizable effect for Drell Yan, but expected to be a small effect for DIS, so additional data are welcome.

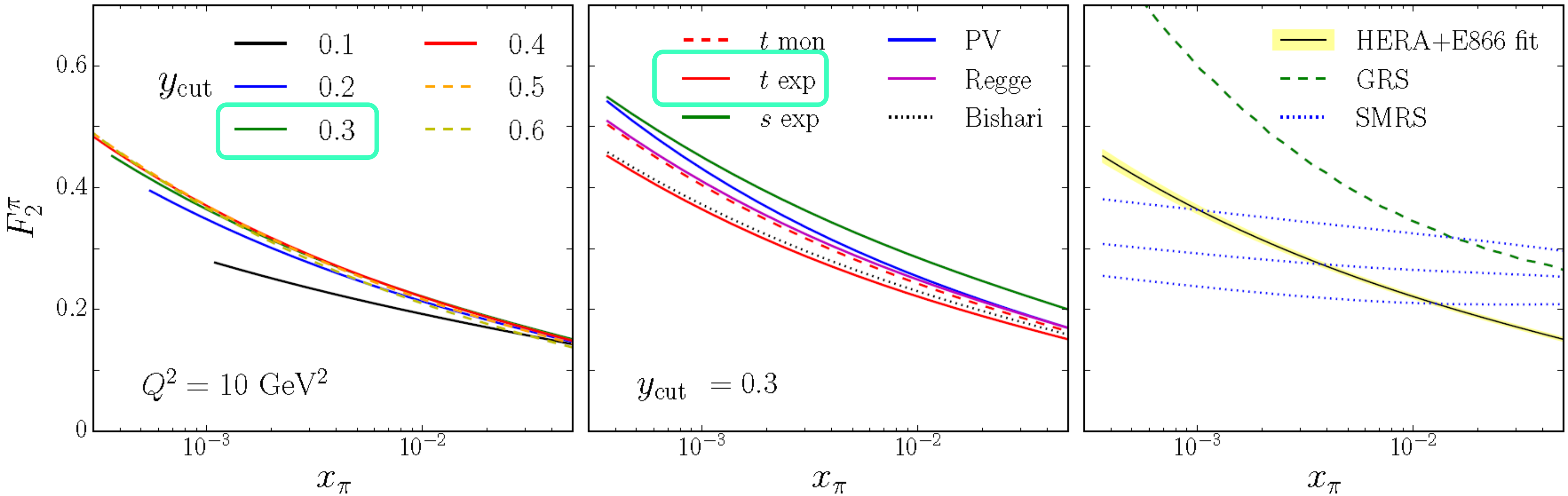
An extraction of the pion structure function F_2^{π} from HERA data

J.R. McKenney, N. Sato, W. Melnitchouk, C-R. Ji, Phys. Rev. **D93** (2016) no5, 054011



- Quality of fit depends on range of y fitted
- To reduce model dependence, fit the value of $y_{\rm cut}$ up to which the data can be described in terms of pion exchange
- Best fits by t-dependent exponential (and t monopole) regulators

An extraction of the pion structure function F_2^π from HERA

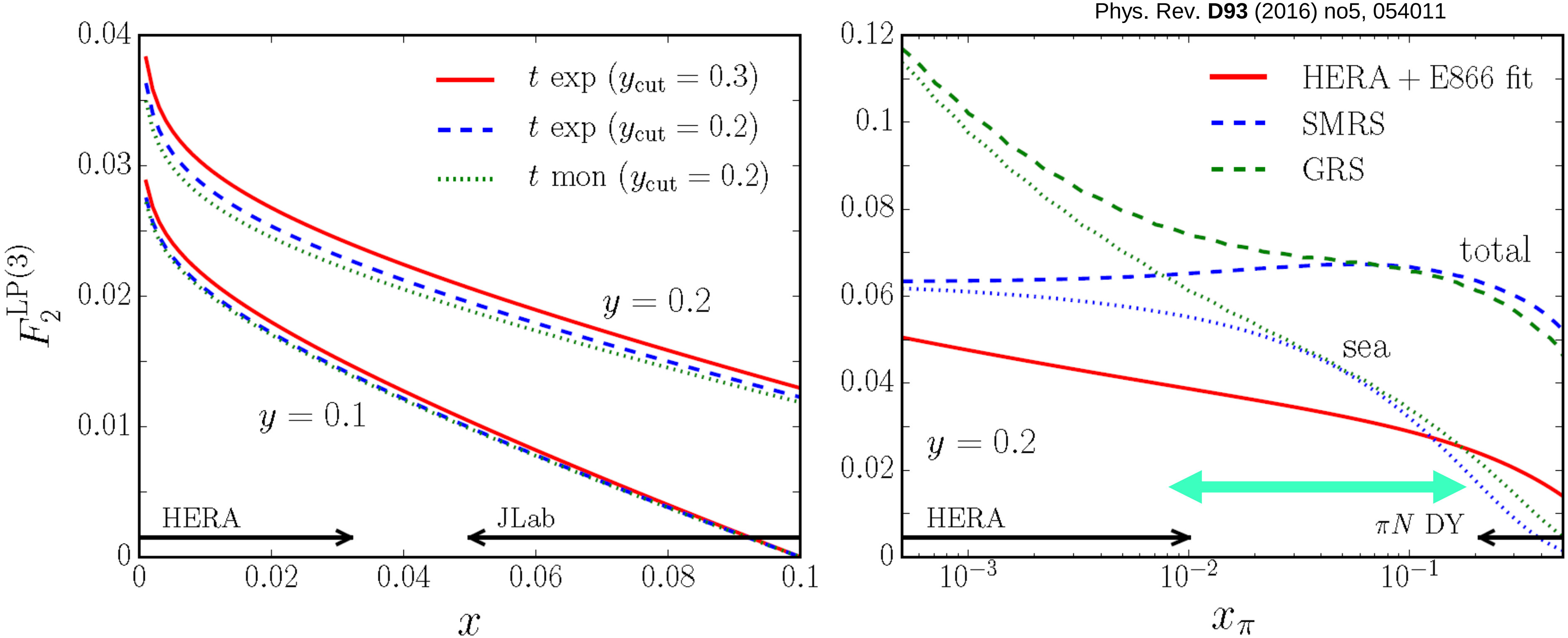


J.R. McKenney, N. Sato, W. Melnitchouk, C-R. Ji, Phys. Rev. **D93** (2016) no5, 054011

- Stable values for $10^{-4} < x_\pi < 10^{-2}$ from combined fit
- Dependence of functional form of πNN form factors is weak
- Shape similar to GRS fit to DY data for $x_\pi > 0.2$, but smaller in magnitude

Constraints from Future DIS Experiments

J.R. McKenney, N. Sato, W. Melnitchouk, C-R. Ji, Phys. Rev. **D93** (2016) no5, 054011

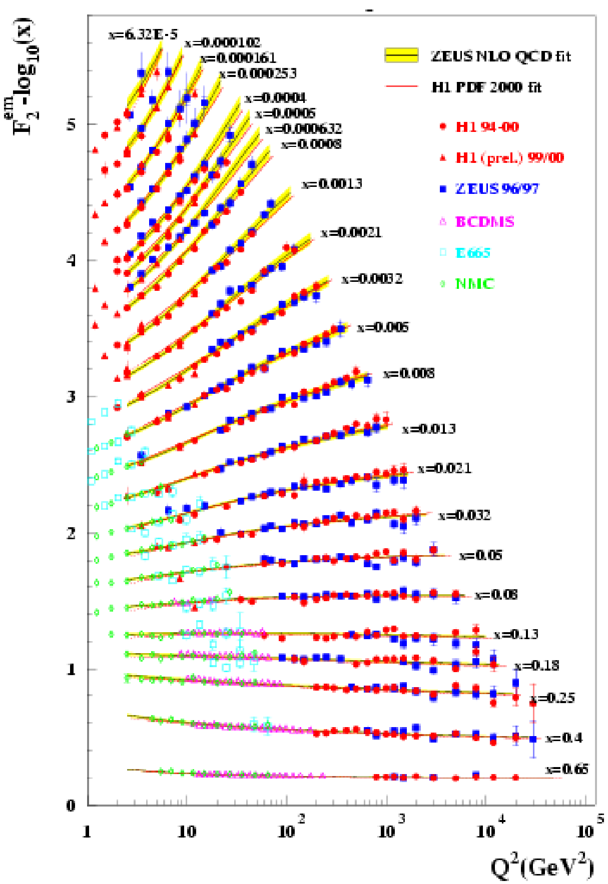


- At larger values of $x_\pi > 10^{-2}$ fit is less reliable – for a more complete QCD-based analysis in terms of valence, sea and gluon PDFs, one needs data for F_2^π over entire region
  - JLab 12 expected to provide constraints at large x (valence region)
  - EIC will fill the gap where sea and gluons contribute

Landscape for p, π, K structure function after EIC

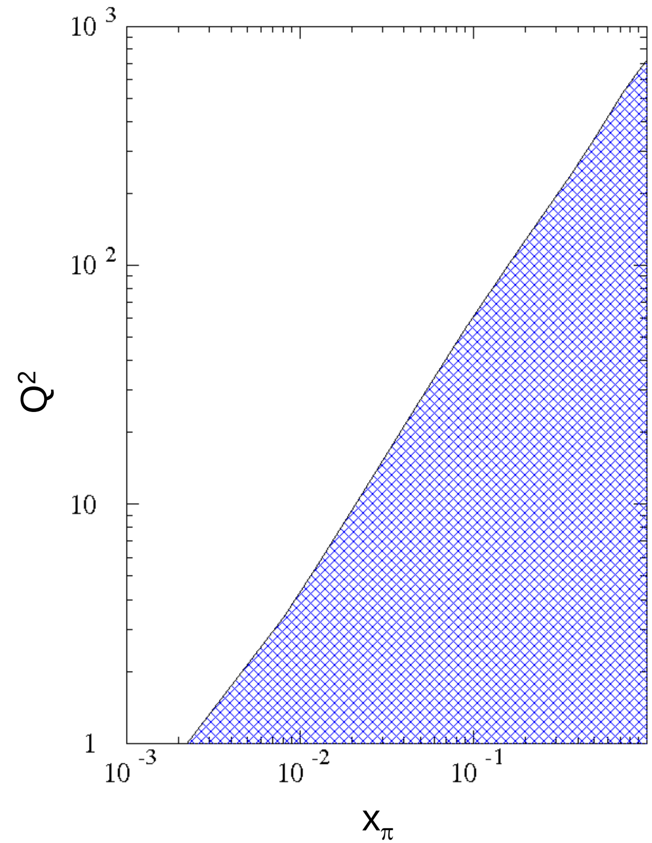
Proton: much existing from HERA

EIC will add:
- Better constraints at large-x
- Precise F_2^n neutron SF data



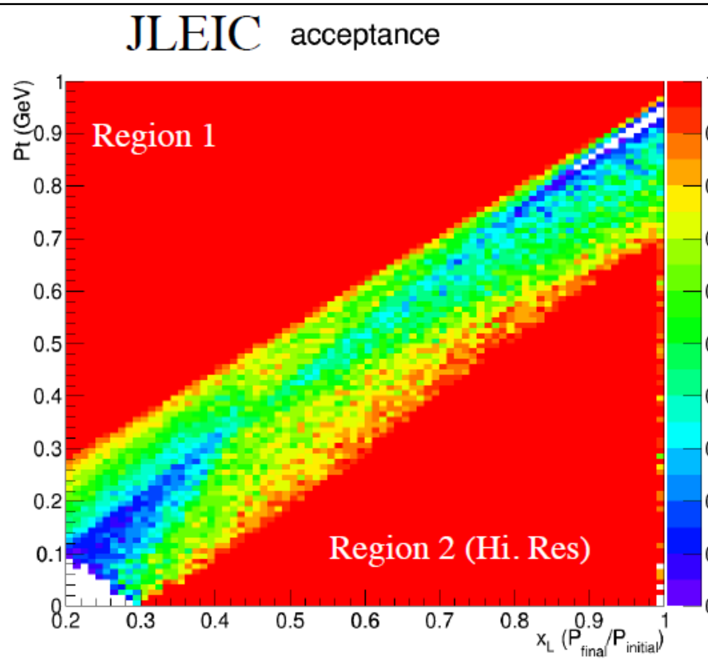
Pion and kaon: only limited data from:
- Pion and kaon Drell-Yan experiments
- Some pion SF data from HERA

EIC will add large (x,Q^2) landscape for both pion and kaon!

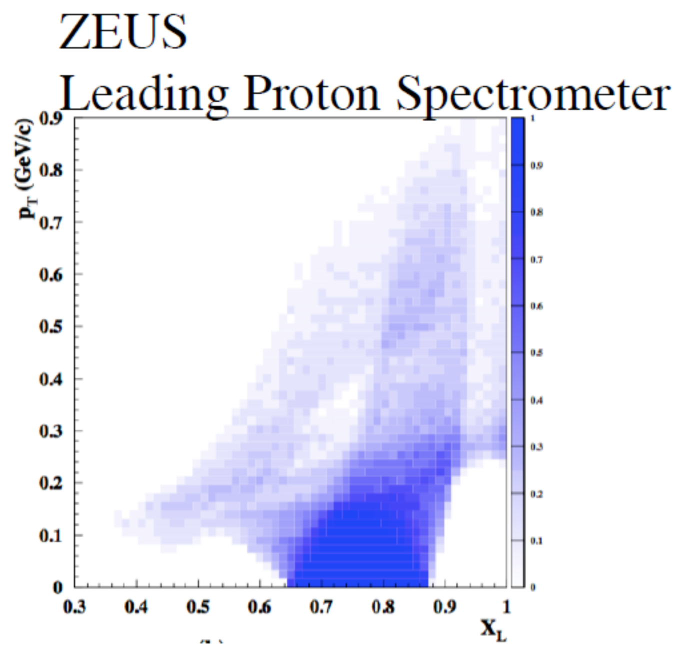


EIC Needs Good Acceptance for Forward Physics!

Example: acceptance for p’ in e + p → e’ + p’ + X



Zhiwen Zhao (Duke)



Acceptance in diffractive peak (X_L>~.98)

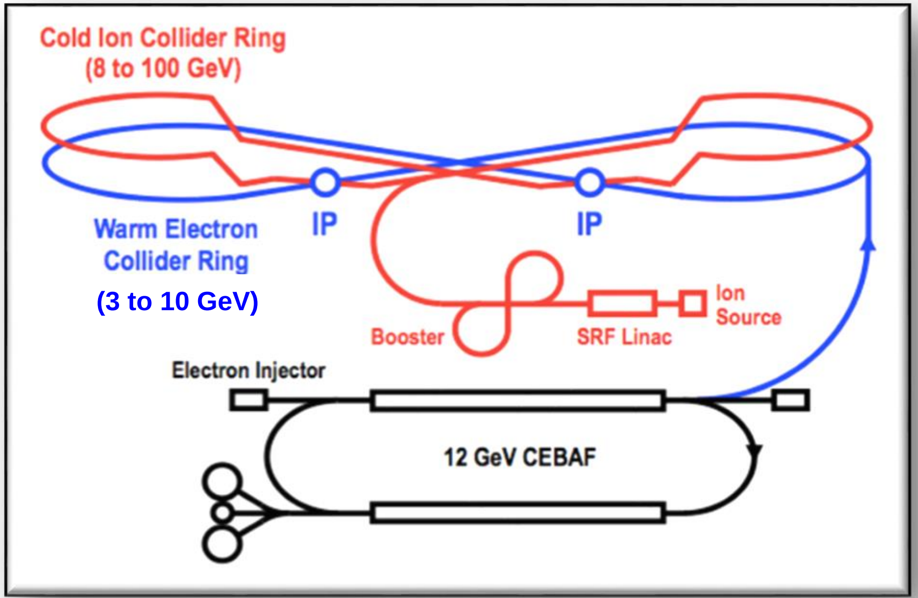
ZEUS: ~2%

JLEIC: ~100% (also covers much higher X_L than ZEUS)

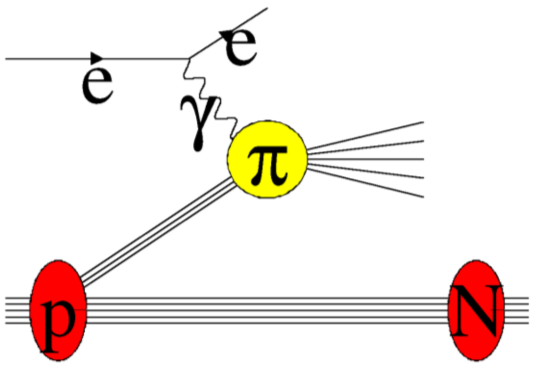
Huge gain in acceptance for forward tagging to measure F_2^n and diffractive physics!!!

Good Acceptance for n, Λ, Σ detection

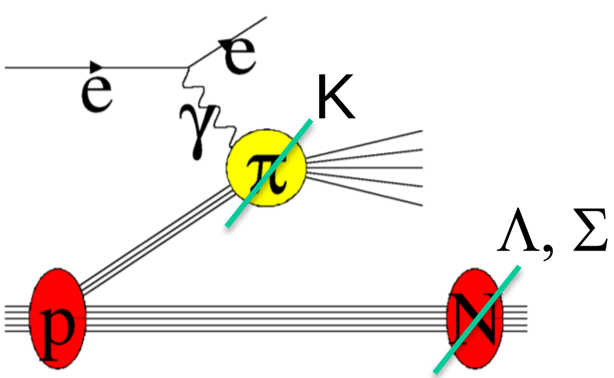
Simulations assume: 5 GeV e^- and 50 GeV p @ luminosity 10^{34} $s^{-1}cm^{-2}$



Sullivan process for pion SF



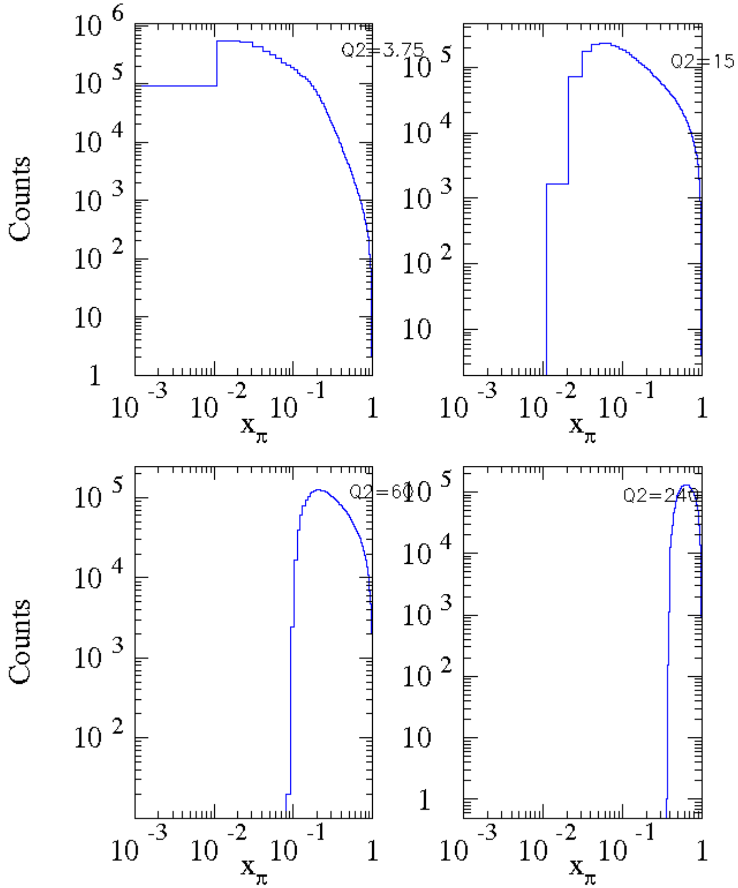
And similar process for kaon SF

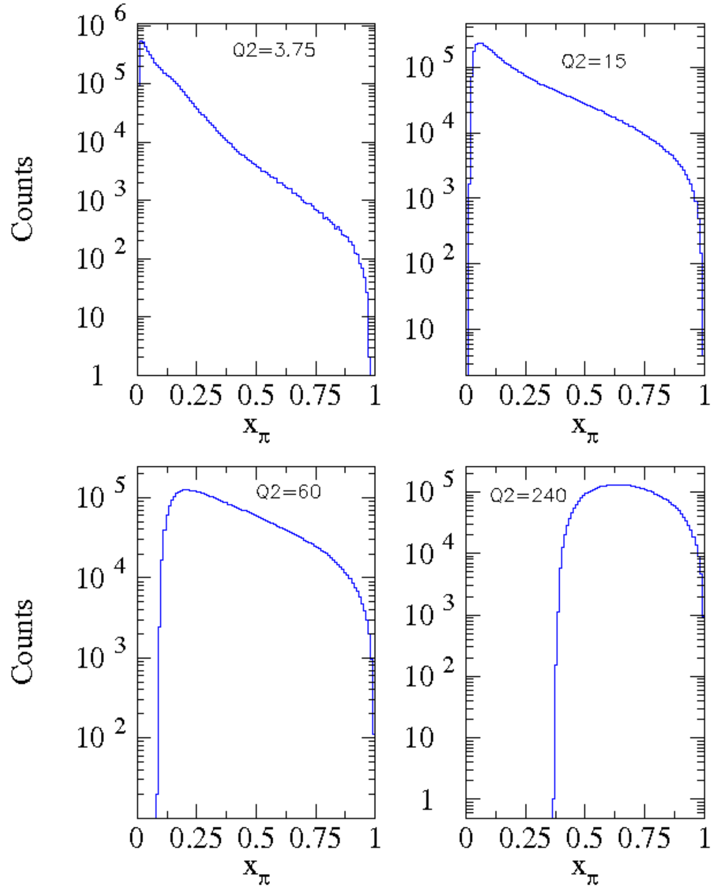


Process	Forward Particle	Geometric Detection Efficiency (at small –t)
$^1H(e,e'\pi^+)n$	N	> 20%
$^1H(e,e'K^+)\Lambda$	Λ	50%
$^1H(e,e'K^+)\Sigma$	Σ	17%

EIC Pion Structure Function Projections

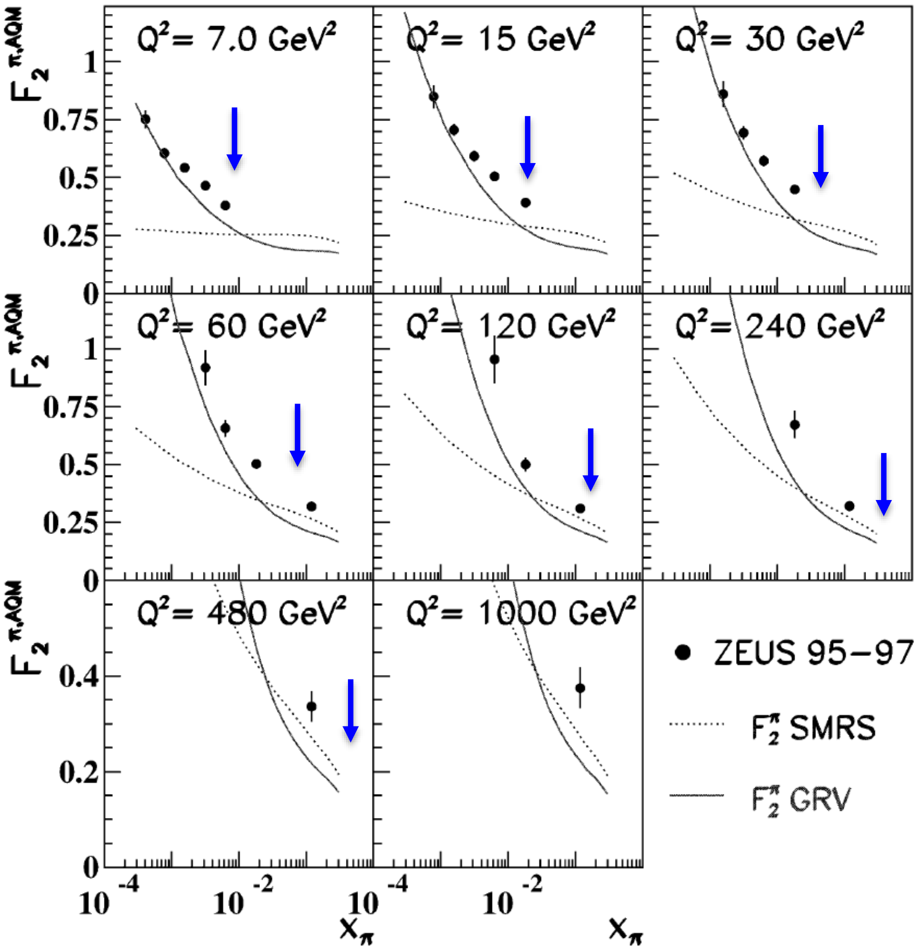
- Counts assume roughly one year of running (26 weeks at 50% efficiency) with 5 GeV electrons and 50 GeV protons at luminosity of $10^{34}\ s^{-1}cm^{-2}$.
- Counts here still need to be multiplied with geometric detection efficiency ~ 20%.





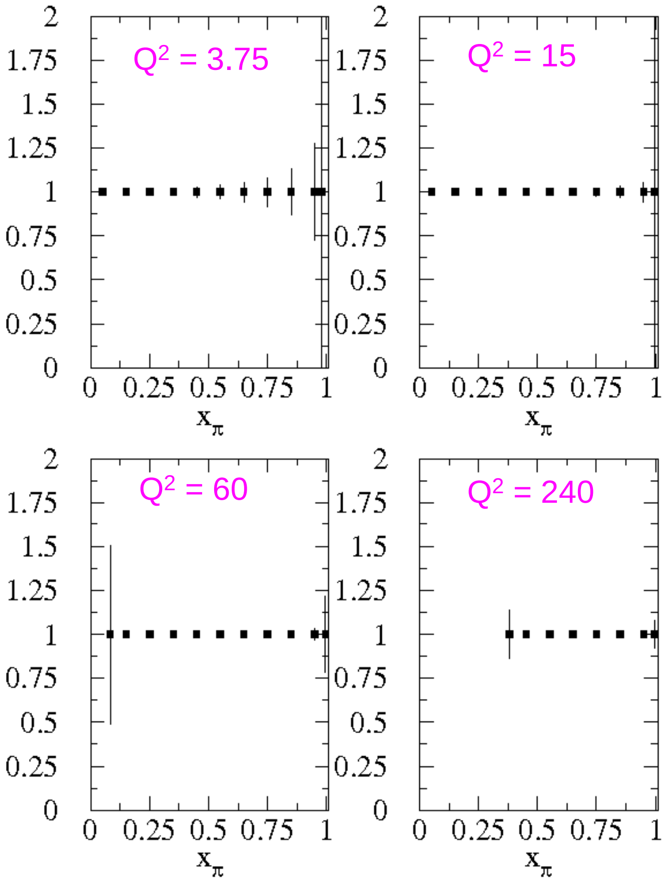
World Data on pion structure function F_2^{π}

HERA



EIC

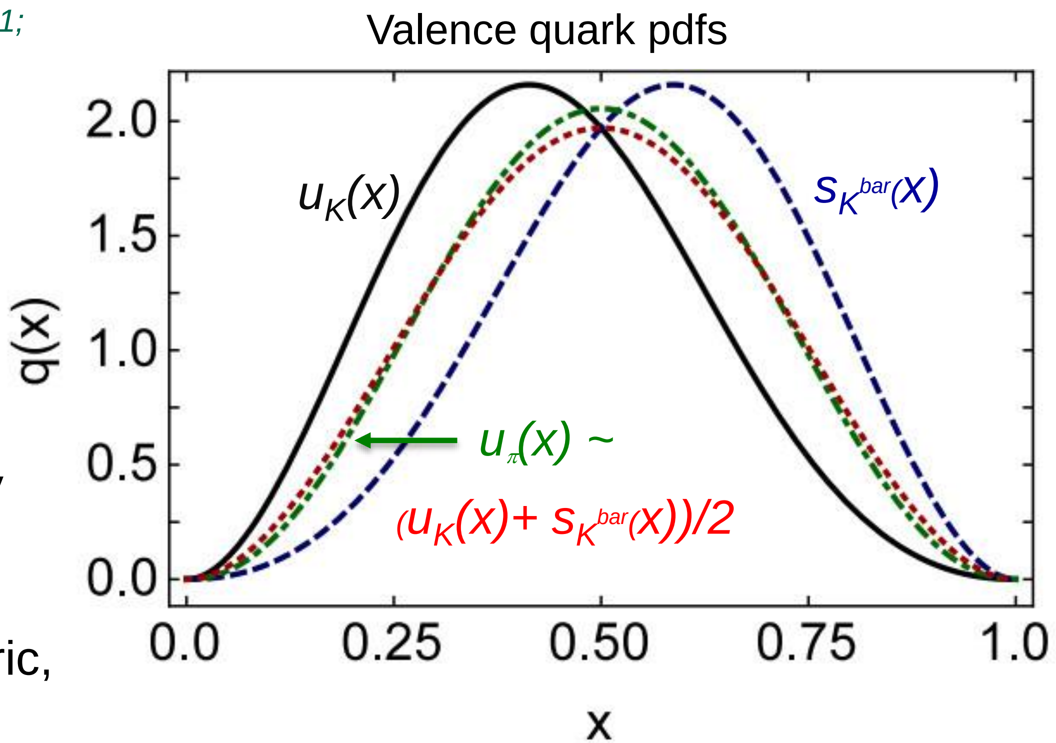
↓ roughly x_{min} for EIC projections



Kaon structure function - valence quarks

*[C.D. Roberts et al, Phys. Rev. **D93** (2016) no.7, 074021; arXiv:1602.01502 [nucl-th]]*

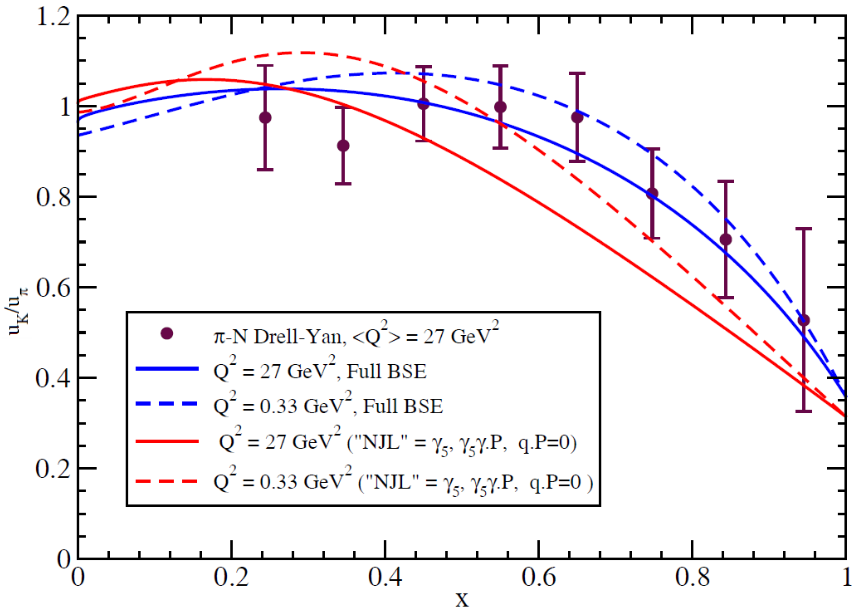
- Pointwise results obtained via reconstruction from (arbitrarily many) computed PDF moments.
- Peak in kaon PDFs shifted 17% away from x=½, *i.e.* the scale of flavor symmetry breaking is set by DCSB (M_s/M_u=1.2).
- $[u_K(x)+s_K^{bar}(x)]/2$ must be symmetric, owing to momentum sum rule. Similar, but not identical to $u_\pi(x)$



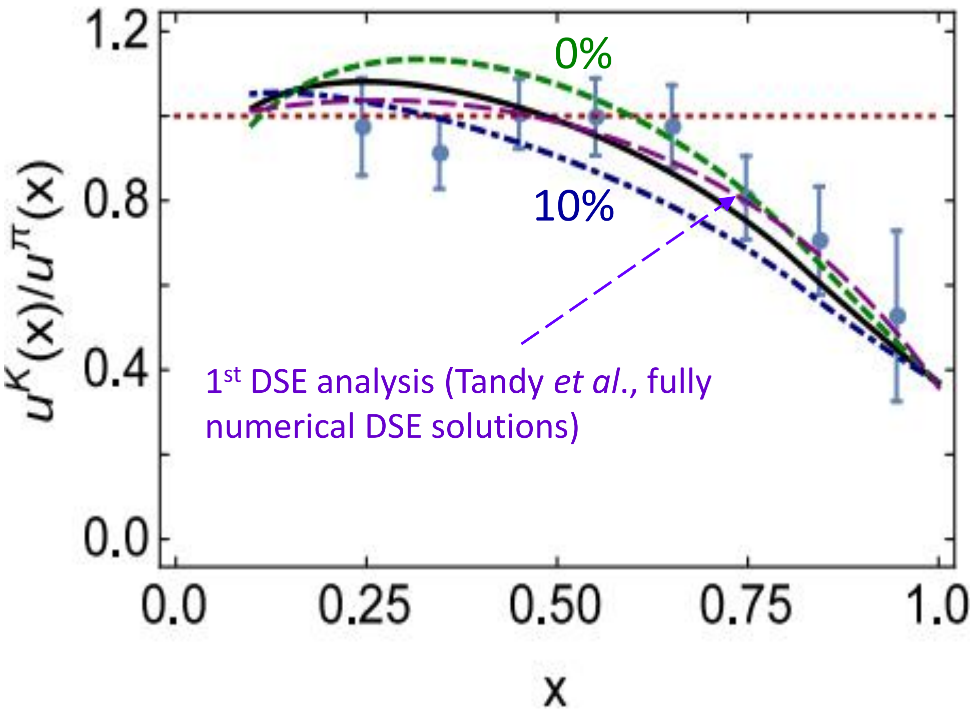
The bulk of this effect may be somewhat trivial and expected since the massive s quark carries most of the momentum of the kaon. *Nevertheless, the effects of gluons will make changes to this effect (see next slide).* This may turn this ratio into an excellent example for textbooks.

u_K/u_π ratios from K/π Drell-Yan Ratios

Predictions of the K/π Drell-Yan ratio based on Bethe-Salpeter Equations (BSE) work well – 1st fully numerical DSE analysis



Gluon content of the kaon



T. Nguyen, A. Bashir, C.D. Roberts and P.C. Tandy, Phys. Rev. C**83** (2011) 062201
Data: Badier *et al.* Phys. Lett. **B93** 354 (1980)

Kaon structure functions – gluon pdfs

Based on Lattice QCD calculations and DSE calculations:

- ❑ Valence quarks carry 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or roughly 65% at the perturbative hadronic scale

- ❑ At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale

Thus, at a given scale, there is far less glue in the kaon than in the pion:

- ➢ heavier quarks radiate less readily than lighter quarks
- ➢ heavier quarks radiate softer gluons than do lighter quarks
- ➢ Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- ➢ Momentum conservation communicates these effects to the kaon's u-quark.

Calculable Limits for Parton Distributions

- Calculable limits for ratios of PDFs at x = 1, same as predictive power of x → 1 limits for spin-averaged and spin-dependent proton structure functions (asymmetries)

$$\left.\frac{u_V^K(x)}{u_V^\pi(x)}\right|_{x\to 1} = 0.37\,, \qquad \left.\frac{u_V^\pi(x)}{\bar{s}_V^K(x)}\right|_{x\to 1} = 0.29$$

- On the other hand, inexorable growth in both pions' and kaons' gluon and sea-quark content at asymptotic Q^2 should only be driven by pQCD splitting mechanisms. Hence, also calculable limits for ratios of PDFs at x = 0, *e.g.*,

$$\lim_{x\to 0}\frac{u^K(x;\zeta)}{u^\pi(x;\zeta)} \overset{\Lambda_{\rm QCD}/\zeta\simeq 0}{\rightarrow} 1$$

The inexorable growth in both pions' and kaons' gluon content at asymptotic Q^2 provides connection to gluon saturation.

Towards Kaon Structure Functions

- To determine projected kaon structure function data from pion structure function projections, we scaled the pion to the kaon case with the *coupling constants* and taking the geometric detection efficiencies into account

*S. Goloskokov and P. Kroll, Eur.Phys.J. A**47** (2011) 112:*

$g_{\pi NN}$=13.1 $g_{Kp\Lambda}$=-13.3 $g_{Kp\Sigma 0}$=-3.5

(these values can vary depending on what model one uses, so sometimes a range is used, *e.g.*, 13.1-13.5 for $g_{\pi NN}$)

- Folding this together: kaon projected structure function data will be roughly of similar quality as the projected pion structure function data for the small-t geometric forward particle detection acceptances at JLEIC – to be checked for eRHIC.

Process	Forward Particle	Geometric Detection Efficiency (at small –t)
^{1}H(e,e'π^+)n	N	> 20%
^{1}H(e,e'K^+)Λ	Λ	50%
^{1}H(e,e'K^+)Σ	Σ	17%

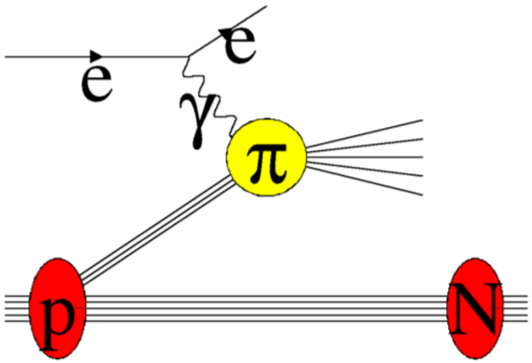
Pion vs. Kaon parton distributions

- Flavor-dependence of DCSB modulates the strength of SU(3)-flavor symmetry breaking in meson PDFs

From: Craig Roberts et al.

- At perturbative hadronic scale ζ_H:
  - valence dressed-quarks carry roughly two-thirds of pion's light-front carried by glue … sea-quarks carry roughly 5%
  - valence dressed-quarks carry approximately 95% of the kaon's light-front momentum, with the remainder lying in the gluon distribution … sea-quarks carry $\simeq$ 0 %
    - heavier s-quarks radiate soft gluons less readily than lighter quarks and momentum conservation subsequently constrains gluons associated with the kaon's u-quark
- Evolving distributions to scale characteristic of meson-nucleon Drell-Yan experiments, ζ=5.2 GeV
  - ratio $u_K(x)/u_\pi(x)$ explained by vastly different gluon content of π & K
- Distributions evolved the distributions to ζ_2 = 2 GeV, which is typically used in numerical simulations of lattice-regularised QCD:
  - Valence-quarks carry roughly half the pion's light-front momentum but two-thirds of the kaon's momentum

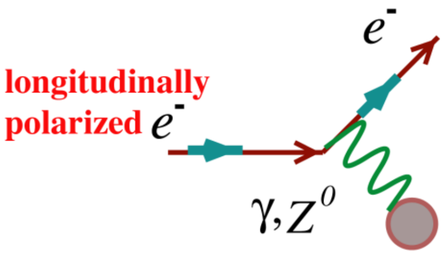
Electroweak Pion and Kaon Structure Functions



- ❑ The Sullivan Process will be sensitive to u and dbar for the pion, and likewise u and sbar for the kaon.
- ❑ Logarithmic scaling violations may give insight on the role of gluon pdfs
- ❑ Could we make further progress towards a flavor decomposition?

1) Using the Neutral-Current Parity-violating asymmetry A_{PV}

2) Determine xF_3 through neutral/charged-current interactions



$$F_2^{\gamma} = \sum_q e_q^2\, x\,(q+\bar{q})$$

In the parton model:

$$F_2^{\gamma Z} = 2\sum_q e_q\, g_V^q\, x\,(q+\bar{q})$$ *Use different couplings/weights*

$$x\,F_3^{\gamma Z} = 2\sum_q e_q\, g_A^q\, x\,(q-\bar{q})$$ *Use isovector response*

$$F_2^{W^+} = 2x\,(\bar{u}+d+s+\bar{c}) \quad F_3^{W^+} = 2\,(-\bar{u}+d+s-\bar{c}) \quad F_2^{W^-} = 2x\,(u+\bar{d}+\bar{s}+c) \quad F_3^{W^-} = 2\,(u-\bar{d}-\bar{s}+c)$$

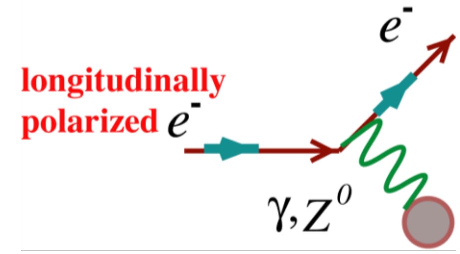
3) Or charged-current through comparison of electron versus positron interactions

$$A = \frac{\sigma_R^{\mathrm{CC},e^+} \pm \sigma_L^{\mathrm{CC},e^-}}{\sigma_R^{\mathrm{NC}} + \sigma_L^{\mathrm{NC}}} \qquad A = \frac{G_F^2\, Q^4}{32\,\pi^2\,\alpha_e^2}\left[\frac{F_2^{W^+} \pm F_2^{W^-}}{F_2^{\gamma}} - \frac{1-(1-y)^2}{1+(1-y)^2}\,\frac{xF_3^{W^+} \mp xF_3^{W^-}}{F_2^{\gamma}}\right]$$

Disentangling the Flavor-Dependence

1) Using the Neutral-Current Parity-violating asymmetry A_{PV}

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



e.g., at $Q^2 << M_Z^2$ (such that $M_Z^2/(Q^2+M_Z^2) \sim 1$)

$$A_{PV} = -e\left(\frac{G_F Q^2}{2\sqrt{2}\,\pi\alpha_e}\right)\left[g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} + \frac{1-(1-y)^2}{1+(1-y)^2}\,\frac{e\,g_V^e\,xF_3^{\gamma Z}}{F_2^{\gamma}}\right] = \frac{e\,G_F Q^2}{4\sqrt{2}\,\pi\alpha_e}\left[a_2(x) + \frac{1-(1-y)^2}{1+(1-y)^2}\,a_3(x)\right]$$

$$a_2(x_A) \equiv -2\,g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \qquad \text{and} \qquad a_3(x) \equiv -2\,e\,g_V^e \frac{x\,F_3^{\gamma Z}}{F_2^{\gamma}}$$

In the parton model: $$a_2(x_A) \equiv -2\,g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \simeq \frac{2\sum_q e_q\,g_V^q\,(q+\bar{q})}{\sum_q e_q^2\,(q+\bar{q})}$$

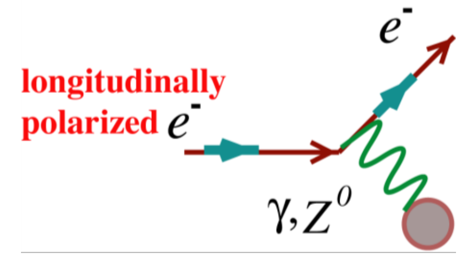
$$a_3(x_A) \equiv -2\,g_V^e \frac{x\,F_3^{\gamma Z}}{F_2^{\gamma}} \simeq \left(1-4\sin^2\theta_W\right)\frac{2\sum_q e_q\,g_A^q\,(q-\bar{q})}{\sum_q e_q^2\,(q+\bar{q})}$$

a_3 is suppressed since $(1 - 4\sin^2\Theta_W) \sim 0$

Disentangling the Flavor-Dependence

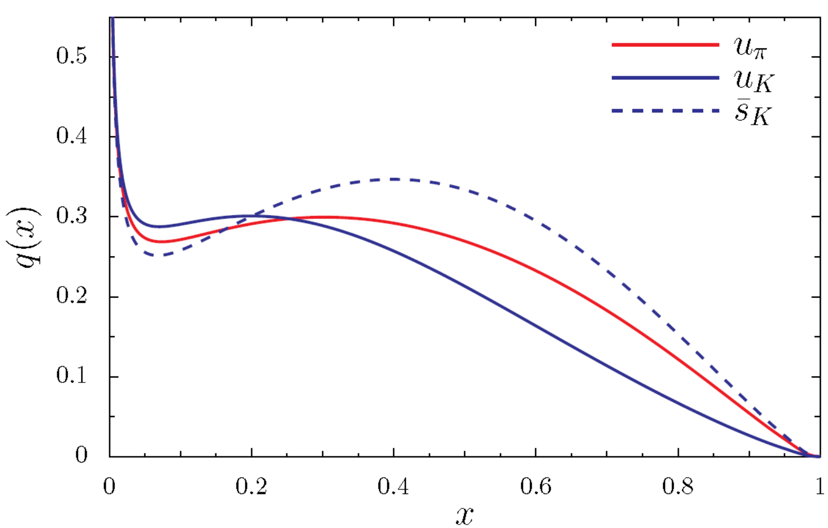
1) Using the Neutral-Current Parity-violating asymmetry A_{PV}

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

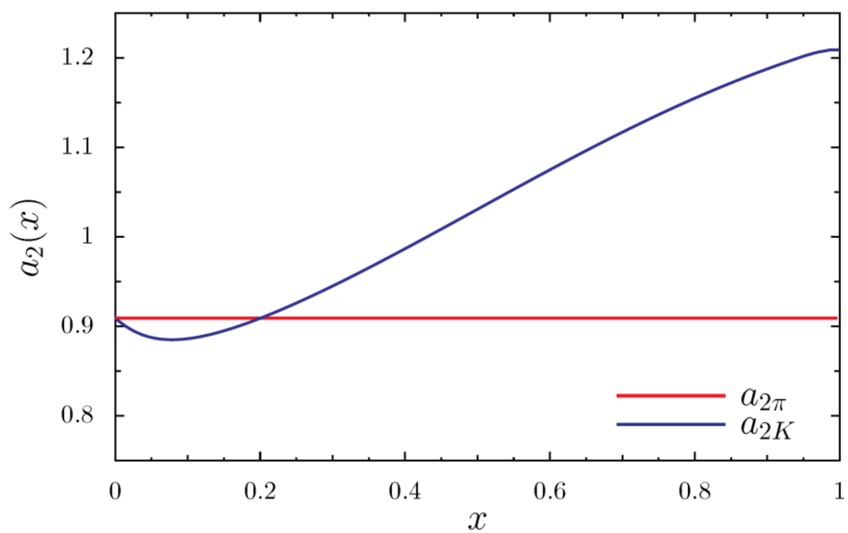


$$a_{2\pi}(x) = \frac{2\sum_q e_q\, g_V^q\,(q+\bar{q})}{\sum_q e_q^2\,(q+\bar{q})} \simeq \frac{6\,u_\pi^+ + 3\,d_\pi^+}{4\,u_\pi^+ + d_\pi^+} - 4\sin^2\theta_W,$$

$$a_{2K}(x) = \frac{2\sum_q e_q\, g_V^q\,(q+\bar{q})}{\sum_q e_q^2\,(q+\bar{q})} \simeq \frac{6\,u_K^+ + 3\,s_K^+}{4\,u_K^+ + s_K^+} - 4\sin^2\theta_W.$$



DSE-based parton distributions in pion and kaon



a_2 picks up different behavior of u and sbar. Flavor decomposition in kaon possible?

Summary

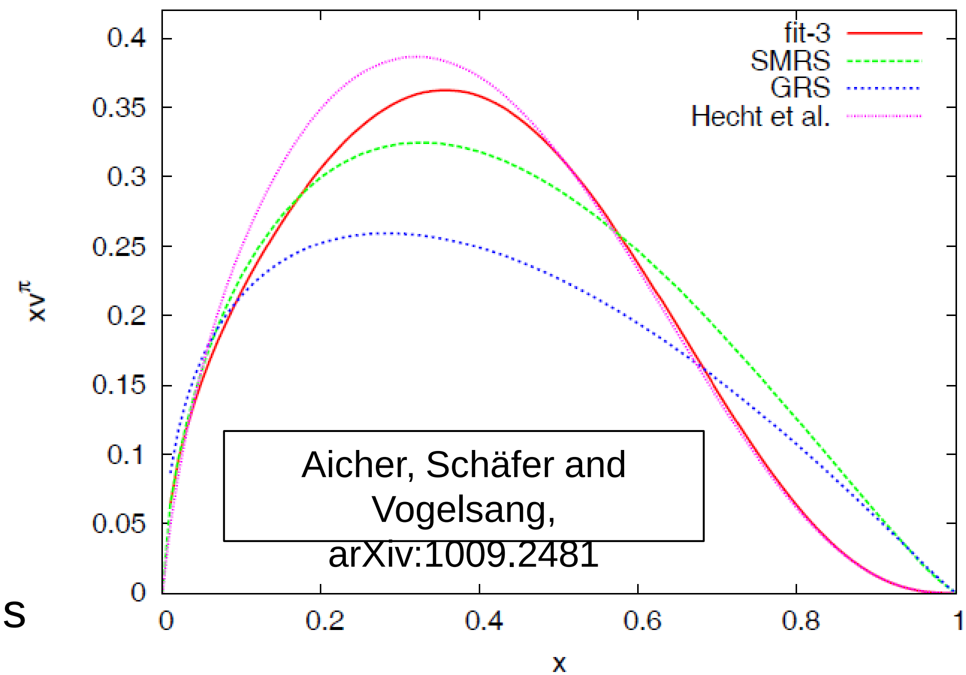
- Nucleons and the lightest mesons - pions and kaons, are the basic building blocks of nuclear matter. We should know their structure functions.
- The distributions of quarks and gluons in pions, kaons, and nucleons will be different.
- Is the origin of mass encoded in differences of gluons in pions, kaons and nucleons (at non-asymptotic Q^2)?
- Some effects may be trivial – the heavier-mass quark in the kaon “robs” more of the momentum, and the structure functions of pions, kaons and protons at large-x should be different, but confirming these would provide textbook material.
- Using electroweak processes, e.g., through parity-violating probes or neutral vs. charged-current interactions, disentangling flavor dependence seems achievable

The issue at large-x: solved by resummation?

- Large x_{Bj} structure of the pion is interesting and relevant
  - Pion cloud & antiquark flavor asymmetry
  - Nuclear Binding
  - Simple QCD state & Goldstone Boson

- Even with NLO fit and modern parton distributions, pion did not agree with pQCD and Dyson-Schwinger

- Soft Gluon Resummation saves the day!
  - JLab 12 GeV experiment can check at high-x
  - Resummation effects less prominent at DIS → EIC's role here may be more consistency checks of assumptions made in extraction



- Additional Bethe-Salpeter predictions to check in π/K Drell-Yan ratio

Origin of mass of QCD's pseudoscalar Goldstone modes

- Exact statements from QCD in terms of current quark masses due to PCAC:
  [Phys. Rep. 87 (1982) 77; Phys. Rev. C 56 (1997) 3369; Phys. Lett. B420 (1998) 267]

$$f_\pi m_\pi^2 = (m_u^\zeta + m_d^\zeta)\rho_\pi^\zeta$$
$$f_K m_K^2 = (m_u^\zeta + m_s^\zeta)\rho_K^\zeta$$

- Pseudoscalar masses are generated dynamically – If $\rho_p \neq 0$, $m_\pi^2 \sim \sqrt{m_q}$
  - The mass of bound states increases as $\sqrt{m}$ with the mass of the constituents
  - In contrast, in quantum mechanical models, *e.g.*, constituent quark models, the mass of bound states rises linearly with the mass of the constituents
  - *E.g.*, in models with constituent quarks Q: in the nucleon $m_Q \sim \frac{1}{3} m_N \sim 310$ MeV, in the pion $m_Q \sim \frac{1}{2} m_\pi \sim 70$ MeV, in the kaon (with s quark) $m_Q \sim 200$ MeV – **This is not real**.
  - In both DSE and LQCD, the mass function of quarks is the same, regardless what hadron the quarks reside in – **This is real**. It is the Dynamical Chiral Symmetry Breaking (DχSB) that makes the pion and kaon masses light.

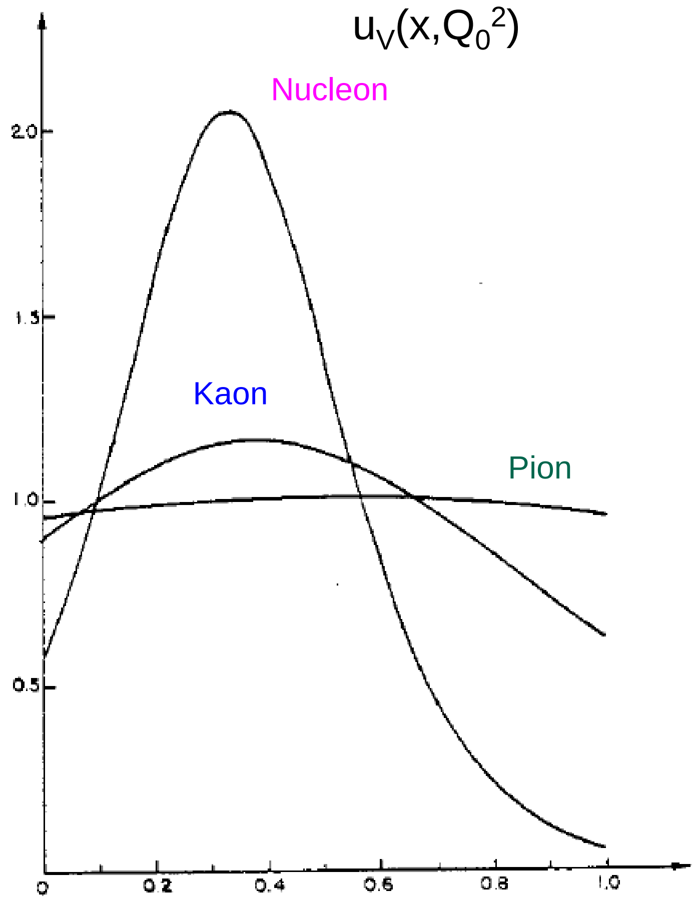
- Assume DχSB similar for light particles: If $f_\pi = f_K \approx 0.1$ and $\rho_\pi = \rho_K \approx (0.5\ \text{GeV})^2$ @ scale $\zeta = 2$ GeV
  - $m_\pi^2 = 2.5 \times (m_u^\zeta + m_d^\zeta)$; $m_K^2 = 2.5 \times (m_u^\zeta + m_s^\zeta)$
  - Experimental evidence: mass splitting between the current s and d quark masses

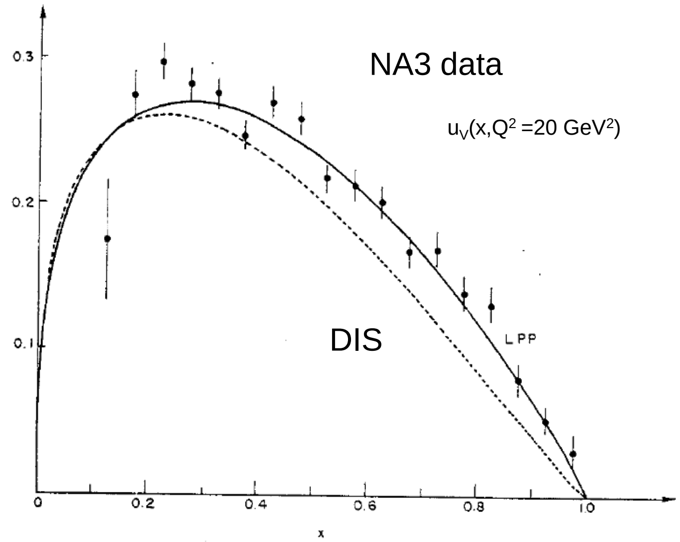
$$m_K^2 - m_\pi^2 = (m_s^\zeta - m_d^\zeta)\frac{\rho^\zeta}{f} = 0.225\,\text{GeV}^2 = (0.474\,\text{GeV})^2 \qquad m_s^\zeta = 0.095\,\text{GeV},\ m_d^\zeta = 0.005\,\text{GeV}$$

$\boxed{\text{In good agreement with experimental values}}$

At some level an old story…

A model for nucleon, pion and kaon structure functions
F. Martin, CERN-TH 2845 (1980)





Predictions based on non-relativistic model with valence quarks only

- pion/kaon differs from proton: 2- vs. 3- quark system
- kaon differs from pion owing to one heavy quark